ECOM - 5260
July 1969
AD

ERBIUM LASER PROPAGATION IN SIMULATED ATMOSPHERES

I. DESCRIPTION OF EXPERIMENTAL APPARATUS AND PRELIMINARY RESULTS

By
R. B. Gomez
and
K. O. White

ATMOSPHERIC SCIENCES LABORATORY
WHITE SANDS MISSILE RANGE, NEW MEXICO

ECOM
UNITED STATES ARMY ELECTRONICS COMMAND

44

ERBIUM LASER PROPAGATION IN SIMULATED ATMOSPHERES

I. DESCRIPTION OF EXPERIMENTAL APPARATUS AND PRELIMINARY RESULTS

By

R. B. Gomez
and
K. O. White

ECOM-5260

July 1969

DA Task 1T061102B53A-18

ATMOSPHERIC SCIENCES LABORATORY
WHITE SANDS MISSILE RANGE, NEW MEXICO

ABSTRACT

Initial results are presented of an experimental study utilizing an absorption cell facility to determine erbium laser propagation characteristics in simulated atmospheres. The facility consists of a 3.3-meter spectrometer coupled to a 20-meter multipass absorption cell. The cell environment can be controlled over a wide range of pressures, temperatures, humidities, and gas concentrations. Absorption measurements were made with path lengths varying from 400 to 1600 meters in a simulated atmosphere consisting of clean dry air. The initial experimentally measured attenuation of 1.54 micron radiation by clean dry air is less than 25% per km. The results include the discovery of a new emission line of the erbium laser at 1.544 microns and the simultaneous emission of lines at 1.544 and 1.536 microns.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the following persons who actively participated in the development of the laboratory facility and in the experimental measurements: Dr. Rufus E. Bruce, for his contributions, as team leader, to all aspects of the program; James B. Mason, for his contributions to the source and detection aspects of the program and for his participation in the experimental measurements; Richard C. Hall, for his contributions to the design and construction of the cell environmental control systems, specifically for the design of the gas handling system; Teddy L. Barber, for his contributions to the design and construction of the experimental apparatus; and Lt. James Veilleux, for calibration of the temperature control system.

In addition, we are indebted to James T. Hall of this laboratory for his helpful technical discussions concerning this program and to Richard Dixon and John Spragins of the White Sands Missile Range Navy machine shop for their help in the construction of the facility. We also wish to acknowledge the assistance of Dr. R. G. Buser of the Institute of Exploratory Research. Grateful thanks are due to Alex Blomerth, Chief of the Atmospheric Physics Technical Area, for his assistance in carrying out the research program.

CONTENTS

FIGURE PAGE

TABLE

1. INTRODUCTION

As the result of a request made by the United States Army Materiel Command, a research program to determine the effects of simulated atmospheres on erbium laser radiation was initiated at the Atmospheric Sciences Office of the Atmospheric Sciences Laboratory, United States Army Electronics Command. This report describes the experimental apparatus and presents the initial results of an investigation of the atmospheric effects on 1.54 micron wavelength laser radiation.

2. SUMMARY OF THEORETICAL INVESTIGATION

Potential atmospheric effects on the propagation of electromagnetic radiation in the 1.54 micron wavelength region were theoretically examined in a previous report (1). It was found that the exact wavelength and width of the laser emission were needed before the effects of the atmospheric absorption lines in the vicinity could be determined. It was reported that the erbium laser may emit anywhere within a $\pm$ .01μ region about 1.54μ and with a spectral width of as much as .005μ. The atmospheric attenuating mechanisms discussed were the following:

(1) Molecular selective line absorption.
(2) Molecular continuum absorption.
(3) Rayleigh scattering.
(4) Aerosol absorption.
(5) Mie scattering.

Utilizing various sources (2-8), an estimate of the attenuation of 1.54 micron radiation was obtained. The data were made applicable to the region of interest by recalculations and interpolations when necessary. Twelve weak absorption bands in the 1.5 to 1.6 micron wavelength region were analyzed including OH, NO, N_2O, O_2, HDO, D_2O, H_2O, and CO_2, with the strongest being the H_2O and CO_2 absorption bands. The main results of the investigation are summarized in Table I and are applicable under the following conditions:

(1) Temperature: $\sim$ 20°C
(2) Relative humidity: $\sim$ 70%
(3) Meteorological Range[†]: $\sim$ 25 km

[†]The meteorological range, V, is that distance for which the transmittance falls to 2%, i.e., $V = 3.912/\alpha$ where α is the attenuation coefficient.

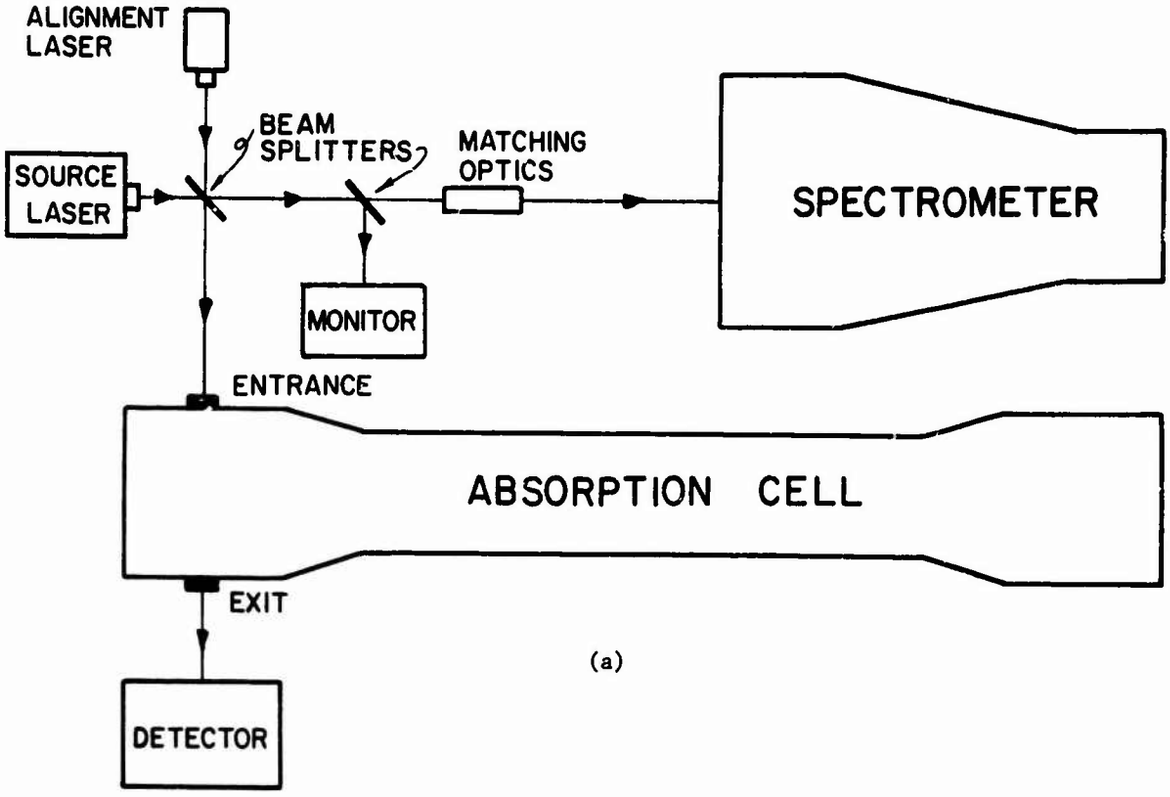
TABLE I. SUMMARY OF THEORETICAL ATTENUATION LOSSES

ATTENUATION	ATTENUATION COEFFICIENT $\alpha(km^{-1})$	LOSS PER KILOMETER
Molecular Selective Line Absorption (Mainly CO_2 and H_2O)	$3x10^{-3}<\alpha<3x10^{-2}$	<3%
Molecular Continuum Absorption (H_2O Vapor)	$1.6x10^{-2}<\alpha<1.6x10^{-1}$	<15%
Rayleigh Scattering	$\alpha<10^{-4}$	<0.1%
Aerosol Absorption	$\alpha<10^{-3}$	<1%
Mie Scattering	$8x10^{-3}<\alpha<1x10^{-1}$	<10%
TOTAL	$2.7x10^{-2}<\alpha<2.9x10^{-1}$	<25%

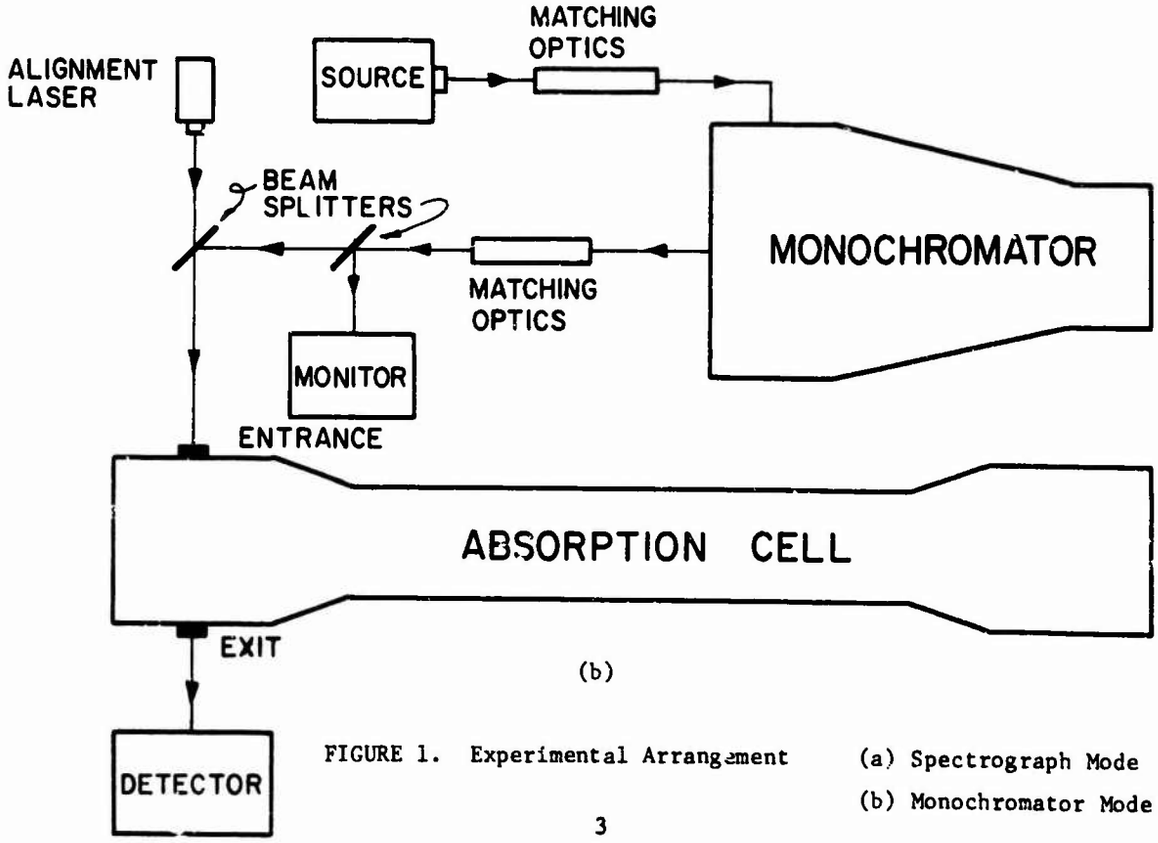
The value listed for aerosol absorption was obtained from measurements of dust particles, common to WSMR, utilizing techniques and instrumentation developed by Hoidale (9) and results from the fact that no absorption bands were observed in the 1.54 micron wavelength region.

3. DESCRIPTION OF EXPERIMENTAL APPARATUS

The Atmospheric Sciences Laboratory (ASL) Absorption Cell Facility consists of a 3.3-meter spectrometer coupled to a 20-meter multipass absorption cell. The cell environment is controlled by a combination of systems which are unique in their design and offer a wide range of pressures, temperatures, humidities, and gas concentrations. In view of the wavelength dependence of the absorption mechanism, the spectral characteristics of the laser output are determined as each absorption measurement is made by arranging the experimental apparatus as shown schematically in Fig. 1a. This arrangement of the apparatus will be



(a)



(b)

FIGURE 1. Experimental Arrangement (a) Spectrograph Mode
(b) Monochromator Mode

referred to as the spectrograph mode of operation. In the monochromator mode of operation (see Fig. 1b) the continuous output of a high energy xenon arc lamp or other source is fed through a scanning monochromator prior to the absorption measurement.

3.1. Multipass Absorption Cell

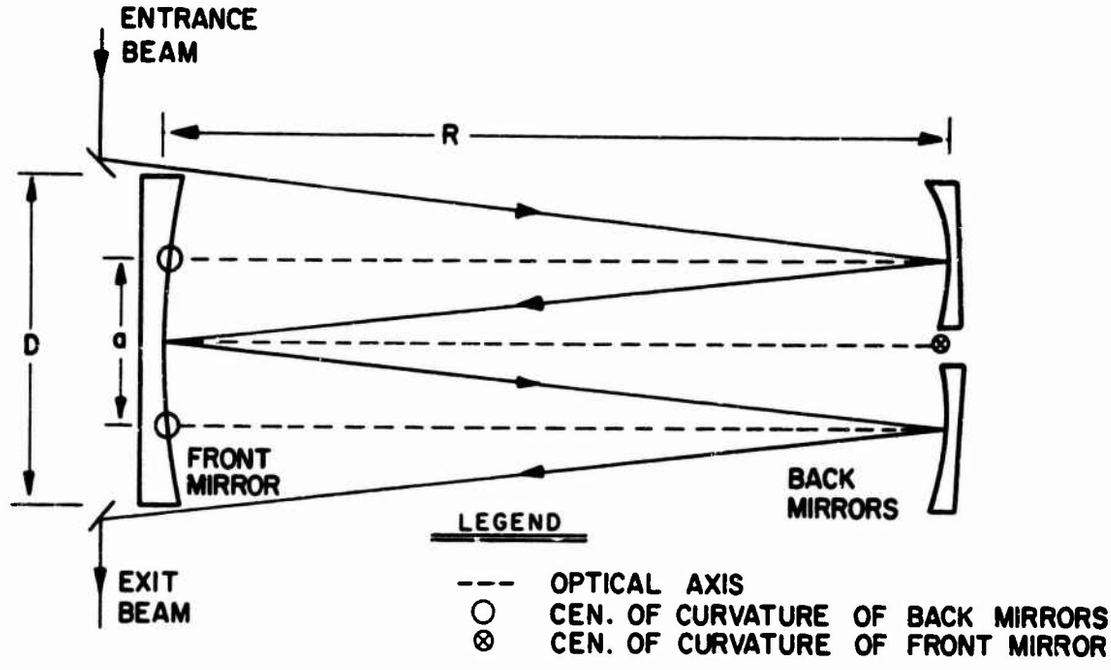
The importance of the multipass absorption cell for investigation of a "simulated atmosphere" is well recognized (10-14). It facilitates the detection and analysis of weakly absorbing components in gas samples. In 1942, White (15) introduced the basic optical principles involved in a multipass gas absorption cell of the type which is discussed here.

The 20 m absorption cell at this laboratory has an inside diameter of 34 cm, a wall thickness of 2 cm, and is fabricated from carbon steel.

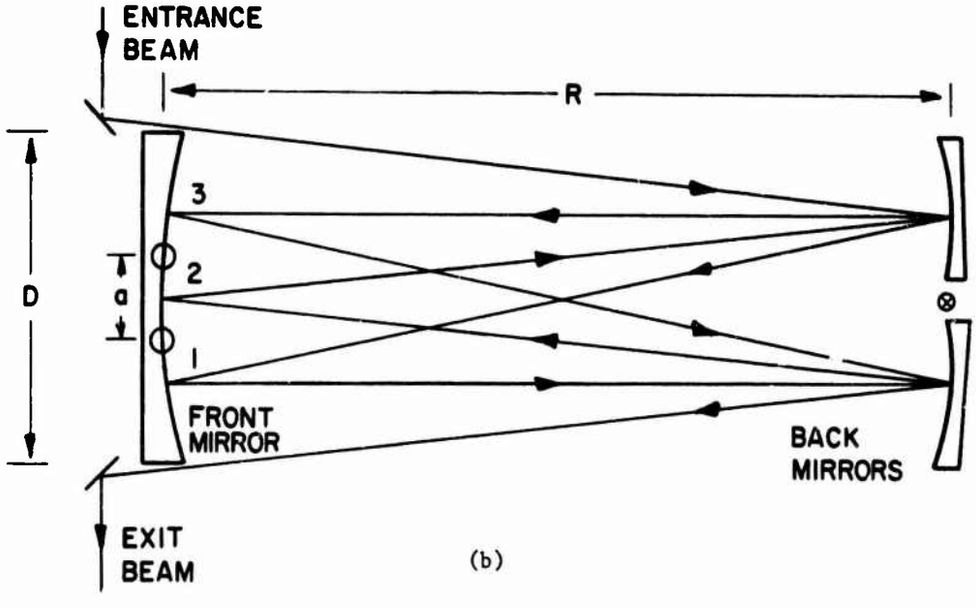
The internal optics of the cell consist of three concave spherical mirrors of equal radii of curvature (20 meters). This optical system is depicted in Fig. 2. The figure illustrates that the centers of curvature of the back mirrors are on the surface of the front mirror, while the center of curvature of the front mirror lies between and in the plane of the back mirrors. The front mirror used in this cell is approximately 21 cm square and each of the back mirrors is 10 cm wide and 21 cm long. Two small diagonal mirrors are used to transfer the electromagnetic radiation into and out of the cell. Figure 2a illustrates that for a single image on the front mirror, the radiation undergoes four passes between the front and back mirrors. In this case the ratio of the distance between the diagonal mirrors, D, to the distance separating the centers of curvature of the back mirrors, a, equals two. The ratio (D/a) can be varied by rotating one (10) or both back mirrors about a vertical axis. (The mirror mechanical adjustment will be half as critical when only one mirror is moved (12).) Increasing the ratio (D/a) results in a greater number of images of the source on the front mirror (see Fig. 2b). The total number of passes, N, can be obtained from the equation

$$N = 2n + 2$$

where n is the number of images on the front mirror. The maximum path length is determined by the number of resolvable images that can be placed on the front mirror. It also depends on the source brightness, the fineness of the mechanical adjustment of the angular separation of the back mirrors, and the fraction of energy loss to reflection. The reflection loss, f_r, is given by



(a)



(b)

FIGURE 2. Optical System of Cell (a) 4 Passes, one Image
(b) 8 Passes, 3 Images

$$f_r = 1 - r^m$$

where r is the reflection coefficient, and m denotes the number of reflections. The number of reflections is related to the number of images by the relation

$$m = 2n + 1$$

The only energy loss in this system due to transmission through glass occurs at the entrance and exit windows.

The principal aberration to be expected in this optical system is astigmatism (15), which can be calculated by several methods (16,17).

The length of the final sagittal image denoted by ΔL_s was calculated, assuming a point source, from a formula of Edwards (16)

$$\Delta L_s = \frac{wb^2}{12R^2}\left(N - \frac{4}{N}\right)$$

where w is the width of the back mirrors illuminated, b is the distance between the entrance and exit images, R is the radius of curvature of the mirrors, and N is the number of passes. The result for 11 images (480-meter path) is

$$\Delta L_s = 1.1 \times 10^{-2} \text{ mm}$$

and for 39 images (1600-meter path)

$$\Delta L_s = 4.2 \times 10^{-2} \text{ mm}$$

Thus for this case the effect will be negligible, and the entrance image will be considered as conserved in form.

3.2. Cell Environment Control Systems

The cell environment control systems are designed to give a wide range of pressures, temperatures, humidities, and gas concentrations. The

pressure control system allows the cell to be operated over pressures ranging from 10^{-3} to $2x10^{3}$ torr. The temperature control system utilizes an electronic device that regulates the temperature of a liquid flowing through copper tubing wrapped around the cell. Presently the temperature control system is designed to provide a temperature stability of the liquid solution of 0.1°C in the range -48°C to 98°C. Multicomponent atmospheres can be simulated in the cell by the gas handling system.

In the heating mode of operation, valves B, D, G, H are open and A, C, E, F, closed (refer to Fig. 3). Water is circulated through a coil of copper tubing submerged inside the expansion tank. This insures that liquid returning to the cold side of the two-way valve is always cooler than the desired set point value. In the cooling mode of operation, valves A, E, F are open and B, C, D, G, H, closed. Valve C is provided as a means of by-passing the control piping and tanks; it remains closed during normal operation.

In order to stabilize the proportion of hot to cold water flowing into the temperature system, an electronic control supplies commands to a Barber-Colman proportional actuator which operates the two-way valve as shown in Fig. 4. If the temperature of the liquid deviates from the value set on the electronic control, the difference causes a change in resistance of the sensing element which unbalances the resistance bridge circuit. The resulting signal is amplified and trips a relay to operate the actuator. The actuator changes the position of the two-way valve until the correct proportion of hot to cold liquid produces an appropriate change in resistance of the sensing element.

The capability of the system to maintain a constant cell temperature was determined by measuring the output of four copper constantan thermocouples installed inside the cell. Three of them were suspended approximately 1/2 inch from the cell wall, one at each end and one in the middle. The fourth thermocouple was placed in contact with the cell wall near one end. This arrangement verified that no temperature gradient existed and that the system was capable of maintaining a constant cell temperature with an accuracy of 0.1°C in the range 35°C to 84°C. With the installation of a second sensing element, the cell temperature can be stabilized to the same accuracy throughout the range -48°C to 98°C.

The humidity and gas composition of the cell atmosphere are controlled by the gas handling system schematically illustrated in Fig. 5. A two-phase process determines water vapor content. Gas from header 2 is passed through dispersion tubes immersed in the saturator bath of the temperature and humidity control, producing a steam whose flow

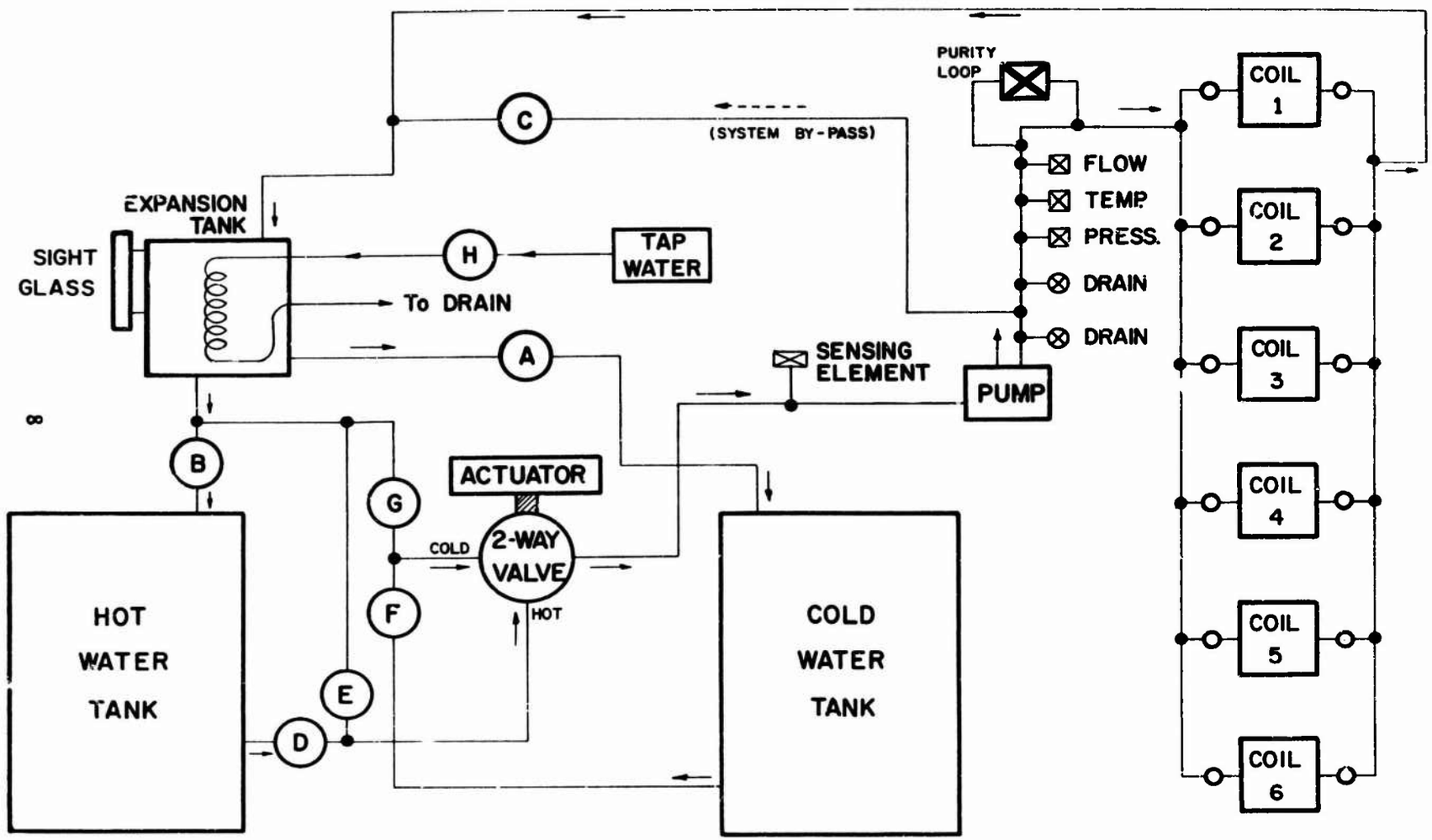


FIGURE 3. Temperature Control System

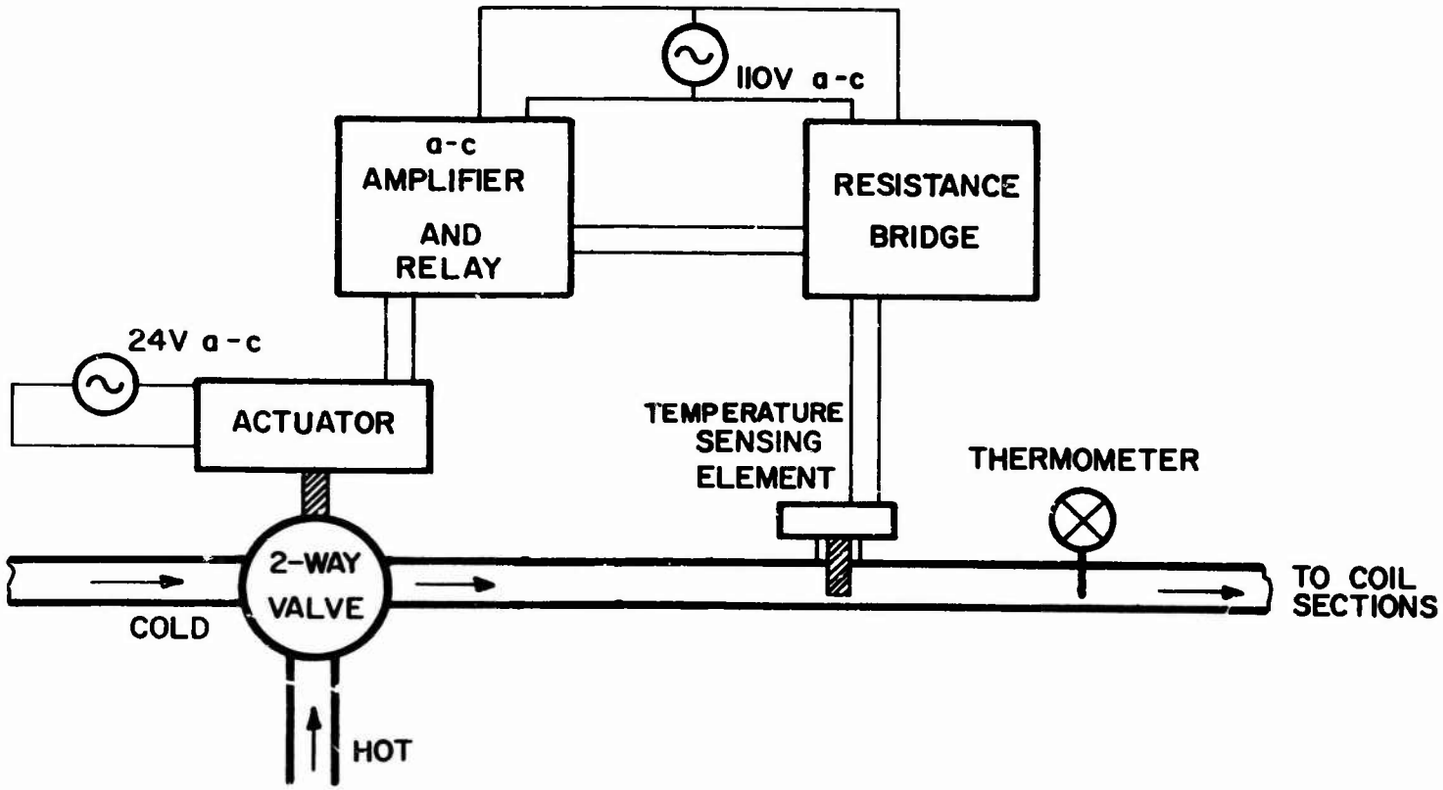


FIGURE 4. Circuit of Temperature Electronic Control

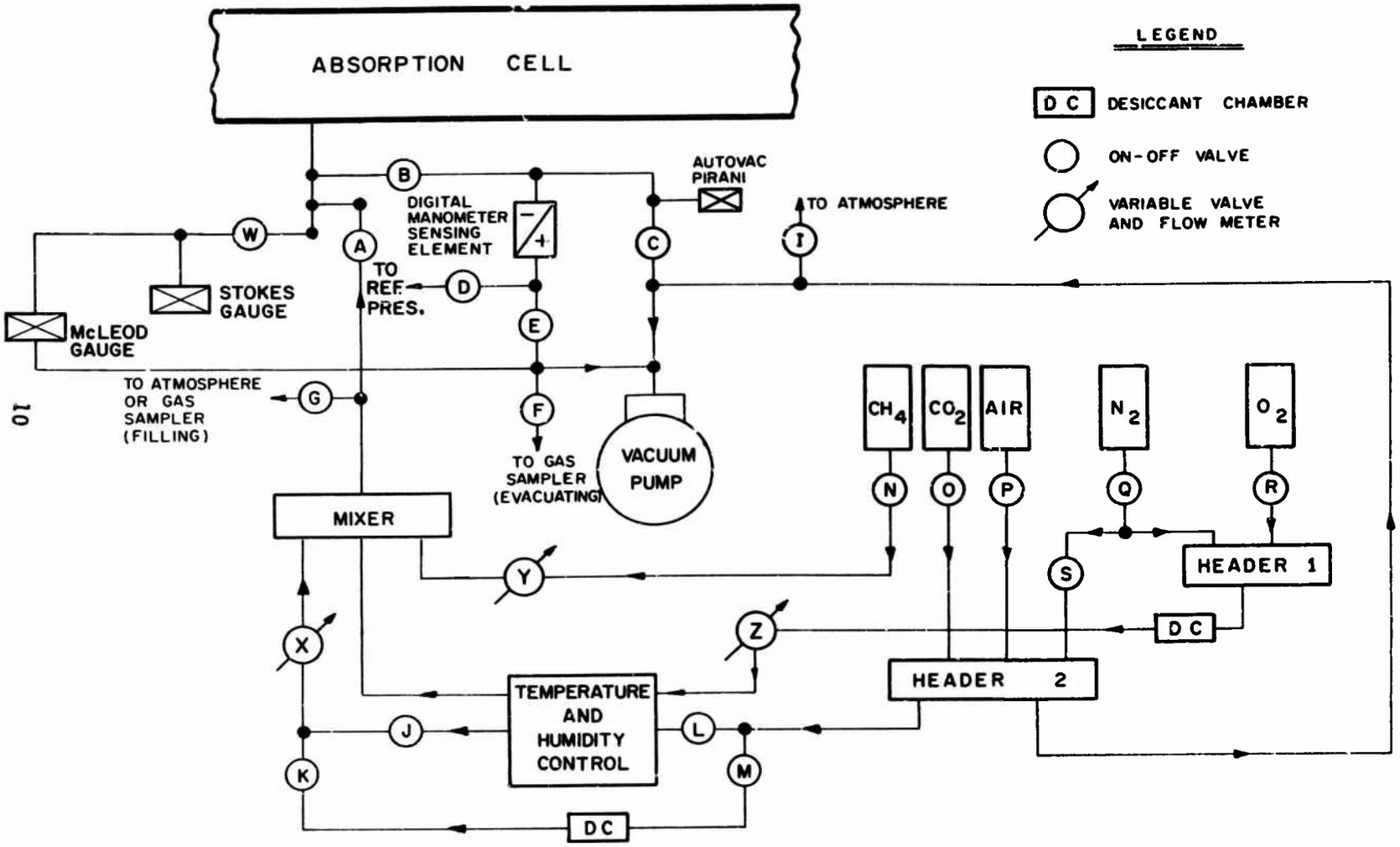


FIGURE 5. Gas Handling System

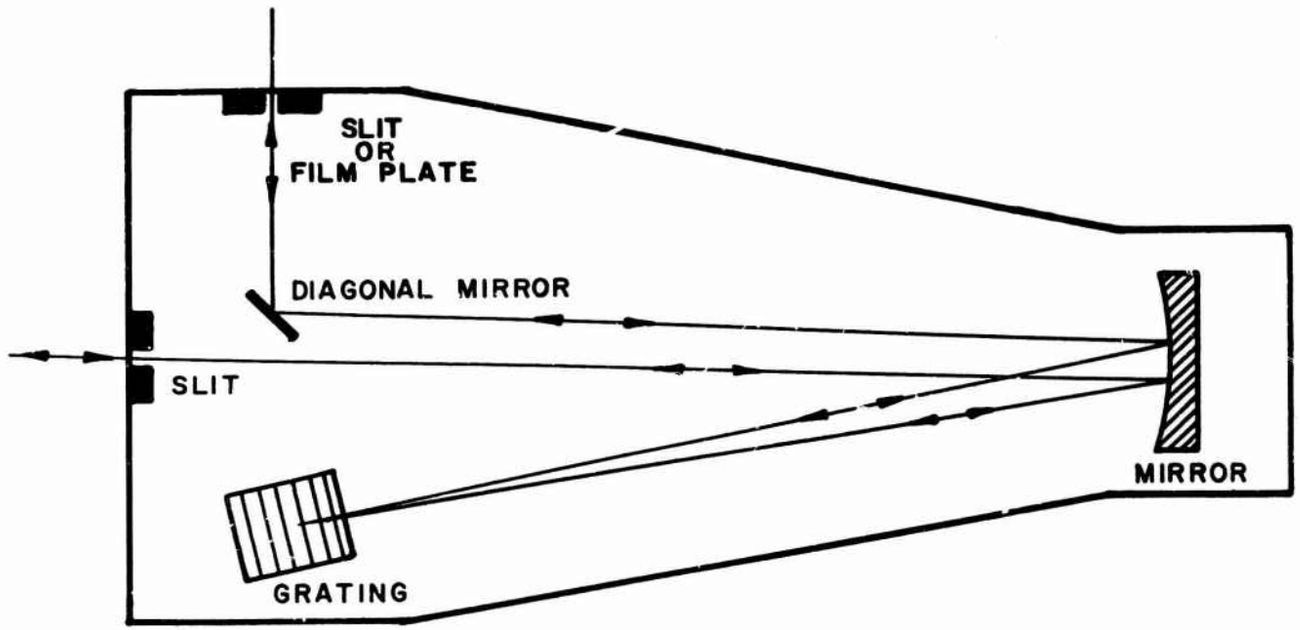
rate is determined by flowmeter X (refer to Fig. 5). Dry gas from header 1, controlled by flowmeter Z, is then mixed with the saturated gas to produce the desired humidity. The temperature of the saturator bath is set to match that of the cell. Due to flowmeter drift, the final value of relative humidity is limited to an accuracy of 2%. The gas handling system is purged by flushing with nitrogen, and a small mechanical pump is used to clear the system of the purging gas and to evacuate gas samplers. By evacuating and filling a 750 ml gas sampler, the composition of the cell atmosphere can be monitored. Infrared absorption spectra run on the sample provide a quantitative analysis of component structure accurate to ±0.5% and determines the accuracy of the system controls over the range of operation.

3.3. Spectrometer

The spectrometer which was constructed in-house uses a Littrow configuration. All the optical components of the spectrometer are mounted on a massive steel frame and mechanically insulated to minimize vibrations. The arrangement of its components and the basic instrument specifications are shown in Fig. 6. The spectrometer can be used both as a spectrograph and as a scanning monochromator. The grating used in this instrument is a 12.5 cm by 25 cm MIT replica on a fused silica blank, with 300 grooves per mm, blazed at 63°. The grating holder is designed to permit scanning about a horizontal axis. The spherical mirror is 30 cm in diameter and has a 3.3 m focal length. At a wavelength of 1.54 microns in 4th order, the reciprocal linear dispersion of this instrument is 0.9 A/mm, and theoretical resolving power of the grating is 300,000 (0.02 cm^{-1}). The supplier of the grating reported that the actual resolving power would be 90% of theoretical.

3.4. Sources

Various laser rods, cavities, flash lamps, and reflectors were utilized in the construction of a suitable erbium laser source which emits at approximately 1.54-micron wavelength. Three erbium-doped phosphate glass laser rods were available. One was a cylindrical rod with a 6 mm diameter and a 55 mm length. Each of the other rods was rectangular with a 3 mm by 6 mm cross section and a 50 mm length. All three rods had polished ends perpendicular to the rod axis and had rough sides. Each of the rods was used in both cylindrical and elliptical cavities. PEK Model XE5-3.00-.250-C helical flash lamps and EG&G Model FX 42 linear flash lamps were available. The helical flash lamp was used with a cylindrical cavity and operated with a nominal input of 1200



SPECIFICATIONS

SPHERICAL MIRROR: diameter = 30.5 cm
focal length = 336.1 cm

GRATING (RULE AREA): width = 12.8 cm
length = 25.6 cm
ruling = 300 lines/mm

FIGURE 6. Spectrometer Configuration

joules.[†] The linear lamp was used with an elliptical cavity and operated with a typical input of 900 joules. The reflectors utilized in the construction of the erbium laser source were one inch in diameter and were mounted in Lansing optical precision mounts. In general the back reflector (non-output end) of each laser design was a 99% reflectance dielectric coated wedge or a prism.[††] The front reflectors used included 50%, 80%, and 90% reflectance aluminum coated flats, a 99.7% reflectance dielectric coated flat (used with the prism back reflector) and a 95% reflectance dielectric coated wedge.

3.5. Detection Methods

In this preliminary study, two methods were employed to detect the spectrographically resolved erbium laser emission. A U. S. Radium Corporation IR sensitive phosphor with both a paper and polyethylene backing was used to detect the onset of laser oscillation. The phosphor, when excited by an ultraviolet source, will darken in the region of incident infrared radiation above a certain threshold energy. The darkened spot produced by the incident laser pulse is observable with the unaided eye. The wavelength of the laser emission was determined with this method by placing the phosphor in the focal plane of the spectrograph and selecting reference lines in the region of the expected laser wavelength.

The second detection method utilized an array of ENL653 germanium photovoltaic detectors placed in the focal plane of the spectrometer. The detectors were biased with 1.5 volts and were used with a fixed resistance in series with the detector.[†††] The signal output from these detectors was displayed on an oscilloscope and photographed.

The arrangement employed to detect the radiation into and out of the cell is illustrated in Fig. 7. The type of detectors used were germanium photovoltaic diodes. Each detector output was displayed on an independent oscilloscope channel and photographed.

[†] A 10,000 joule maximum output power supply was used.

[††] The prism was incorporated in a TRG model 104A laser head capable of Q-switch operation.

[†††] The resistance used varied from 10 to 1000 ohms.

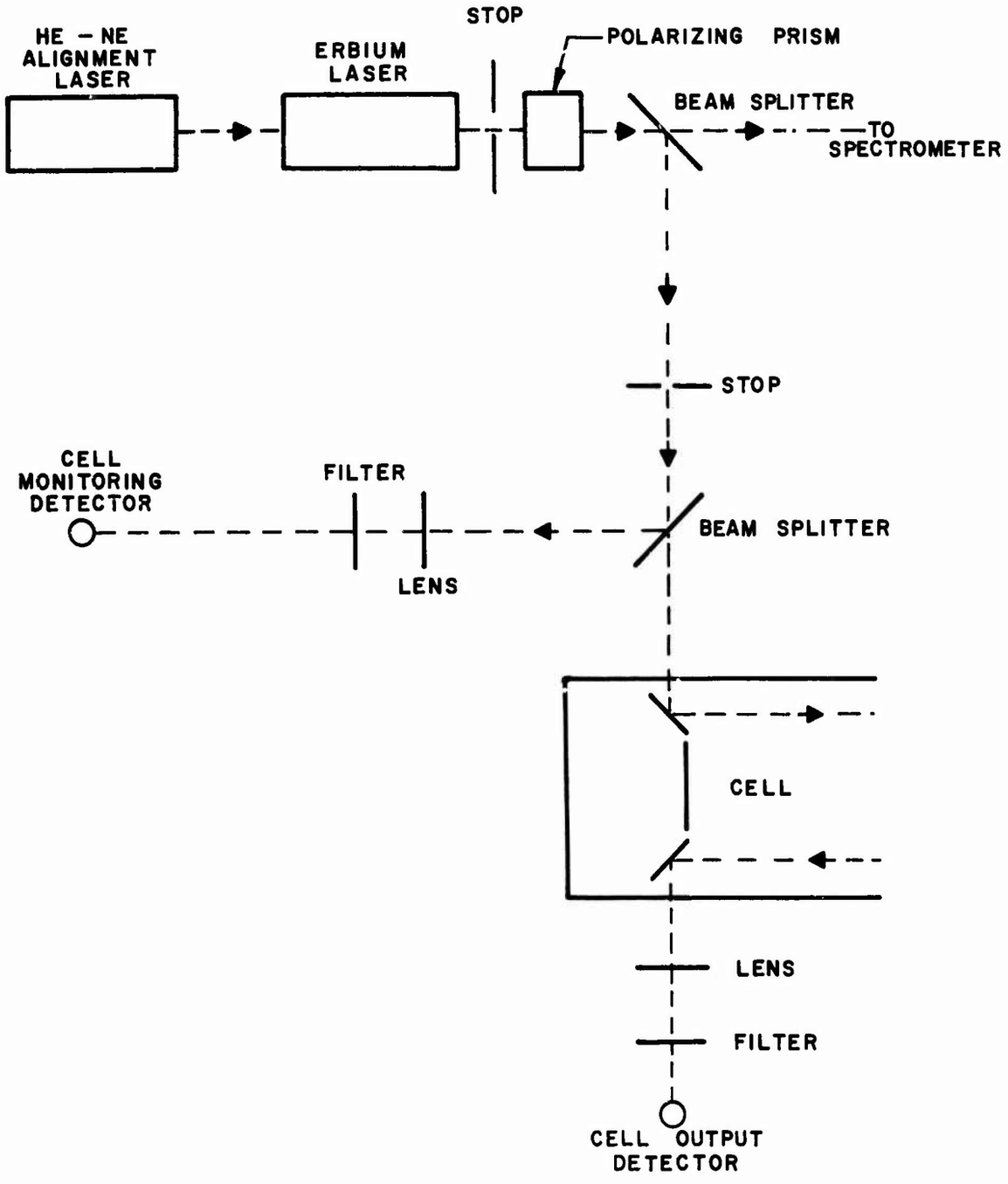


FIGURE 7. Experimental Arrangement with Erbium Laser

4. EXPERIMENTAL PROCEDURES

4.1. Laser Procedure

The spectral characteristics of the laser source are required for adequate analysis of absorption measurements. Therefore the spectrum of the laser emission was determined simultaneously with each absorption measurement. The arrangement of the experimental apparatus used for these measurements is shown schematically in Fig. 7. Since the erbium laser output is pulsed and invisible, a one milliwatt 0.6328μ wavelength helium-neon laser was used for alignment. The laser configuration using the cylindrical cavity with the 5000 joule maximum output helical flash lamp resulted in the most dependable emission. For some cases a polarizing Wollaston prism was used to obtain a linearly polarized beam. Filters (centered at 1.54μ with a 0.05μ bandpass) were employed to eliminate flash lamp light.

The wavelength of the erbium laser emission was calculated by noting its position with respect to four reference lines having a 200 mm spread in the focal plane of the spectrometer. These known lines of wavelengths 0.6096μ, 0.6128μ, 0.6143μ, and 0.6163μ (in 10th order) were isolated from a neon source with a 0.0075μ bandpass filter centered at 0.6130μ. The grating angle α_i for each of these lines was calculated from the grating equation by setting the angle of incidence equal to the angle of reflection, i.e., a Littrow configuration, so that

$$\alpha_i = \arcsin \frac{n \lambda_i}{2d} \qquad i = 1,2,3,4$$

where n is the order, λ the wavelength, and d the spacing between rulings. For the case of the erbium laser, the 1.544μ line in 4th order was near the neon 0.6163μ line in 10th order. Hence, with the grating positioned at the grating angle α_4, corresponding to the 0.6163μ neon line λ_4, the laser wavelength λ was found by setting $\alpha = \alpha_4$ and $\beta = \alpha_4 + \Delta\alpha$ in the grating equation so that

$$\lambda = \frac{d}{n} [\sin \alpha_4 + \sin (\alpha_4 + \Delta\alpha)].$$

The quantity $\Delta\alpha$ is given by $\Delta L/f$ where ΔL is the distance, in the spectrometer focal plane, between the positions of λ and λ_4 and f is the focal length of the collimating mirror.

An indication of the spectral half-width of the erbium laser output was obtained by scanning its wavelength region in the focal plane of the spectrograph with the photovoltaic germanium diodes.

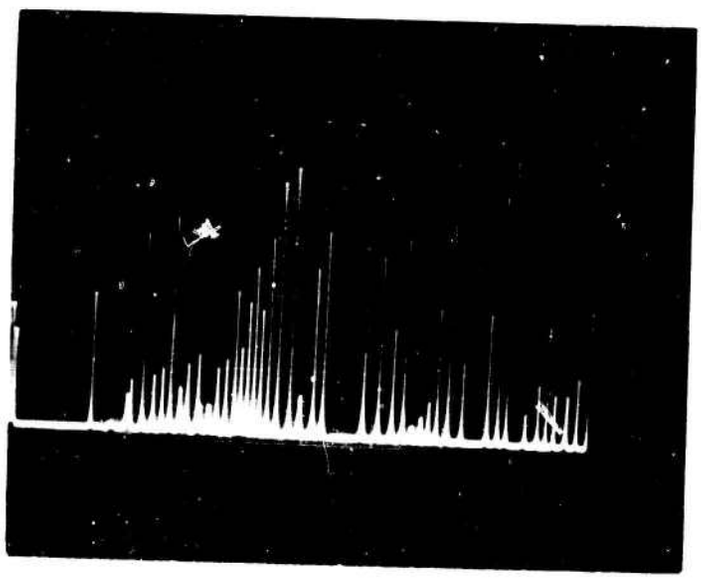
4.2. Absorption Cell Procedures

When the absorption cell was used for the erbium laser propagation studies, the procedures followed permitted the separate measurement of the various attenuating mechanisms present; i.e., cell optics, scattering, and absorption. In preparation for measurements, the cell was outgassed for several hours by raising the temperature to about 95°C and lowering the pressure to about 10^{-2} torr. The constant energy losses (reflection and absorption losses due to the cell optics) were measured at selected temperatures and various path lengths by determining the transmission of the laser while the cell pressure was maintained at about 10^{-2} torr. An estimate of the attenuation due to scattering in the cell was obtained by measuring the transmission in a nonabsorbing gas. For this case, the cell was filled with clean dry nitrogen (no absorption in 1.5 micron wavelength region) to ambient pressure. Any increase in the attenuation, over the corresponding constant energy loss case, can be attributed to Rayleigh scattering by the nitrogen and Mie scattering by particulates. Although the scattering was expected to vary from gas sample to gas sample, the Rayleigh scattering was accurately calculated for the various gases used, and the Mie scattering (from suspended particles picked up from the cell walls) was shown to be negligible. In practice, the results obtained from the nitrogen case were not significantly different from the vacuum case. Finally the cell was filled with the gas or gas mixture of interest and the absorption determined. The measurements were repeated for different path lengths, pressures, and temperatures. Typical data obtained are shown in Fig. 8. The absorption coefficient was obtained by the procedure outlined in the next section.

5. THEORY OF ANALYSIS

Each laser pulse consisted of a sequence of spikes as shown in Fig. 8. The individual spike heights of these pulses were measured before and after transmission, taking into account the different gain settings for the input and output detector channels. The intensity of a transmitted spike I_i^t was related to the intensity of the corresponding incident spike intensity I_i^o by the Lambert-Beer's law

$$I_i^t = I_i^o F_i \exp [-k_i(\nu)x]$$



Source: Erbium Laser

Sweep Rate: 0.1 millisecond per division

FIGURE 8. Typical Absorption Cell Data

where $k_i(\nu)$ is the extinction coefficient at frequency ν, F_i the reflection and absorption losses due to cell optics and x the path length.

Ideally each spike height H_i is proportional to the detector voltage which in turn is proportional to the intensity I_i. It follows that

$$\frac{R_i^o \, H_i^t}{R_i^t \, H_i^o} = F_i \exp\left[-k_i(\nu)x\right]$$

where the superscript o designates input, the superscript t designates transmission, and R_i is the detector characteristic for the i^{th} spike. Since the extinction coefficient $k_i(\nu)$ is the sum of the absorption coefficient $\alpha_i(\nu)$ and the scattering coefficient $\beta_i(\nu)$, then the expression solved for the $\alpha_i(\nu)$ becomes

$$\alpha_i(\nu) = -\beta_i(\nu) - \frac{1}{x} \ln\left(\frac{R_i^o \, H_i^t}{R_i^t \, H_i^o \, F_i}\right)$$

In the case of transmission through vacuum, denoted by the superscript v, the absorption and scattering coefficients vanish, and one has

$$F_i^v = \frac{R_i^{ov} \, H_i^{tv}}{R_i^{tv} \, H_i^{ov}}$$

Under the assumption of constant energy losses due to optics (no time-varying energy loss due to optics from spike to spike in each measurement), one has

$$F_i^v \simeq \overline{F^v}$$

where the overbar denotes the average over M different spikes. In the case of transmission through the absorbing gas mixture, denoted by the superscript g, we see that the average absorption coefficient for M different spikes is given by

$$\overline{\alpha^g(\nu)} = -\overline{\beta^g(\nu)} - \frac{1}{Mx} \ln \prod_{i=1}^{M} \left(\frac{R_i^{og} H_i^{tg}}{R_i^{tg} H_i^{og} F_i^g} \right)$$

Since the Rayleigh scattering for the gases in question was calculated to be small and the particle concentration measured was small so the Mie scattering was negligible, then

$$\overline{\beta^g(\nu)} \simeq 0$$

Now, within the linear range of the detectors† one has

$$R_i^{ov} \simeq \overline{R^{ov}}, \quad R_i^{og} \simeq \overline{R^{og}}$$

$$R_i^{tv} \simeq \overline{R^{tv}}, \quad R_i^{tg} \simeq \overline{R^{tg}}$$

and again assuming constant energy losses due to optics, one has

$$F_i^g \simeq \overline{F^g}$$

Hence the expression for $\overline{\alpha^g(\nu)}$ becomes

$$\overline{\alpha^g(\nu)} = -\frac{1}{Mx} \left[\ln \prod_{i=1}^{M} \left(\frac{H_i^{tg}}{H_i^{og}} \right) + M \ln \left(\frac{\overline{R^{og}}}{\overline{R^{tg}}\ \overline{F^g}} \right) \right]$$

If no systematic errors are introduced in going from the transmission measurements in vacuum to those in the absorbing gas mixture, then it follows that

---

†The linear range of the input and output detectors was determined by beam splitting the laser beam onto the two detectors with equal paths between the beam splitter and each detector. The output of one detector was plotted versus the output of the other as the beam in one of the two paths was attenuated with neutral density filters.

$$\overline{F^g} = \overline{F^v},\ \overline{R^{og}} = \overline{R^{ov}},\ \text{and}\ \overline{R^{tg}} = \overline{R^{tv}}$$

so that the expression for $\overline{\alpha^g(\nu)}$ reduces to

$$\overline{\alpha^g(\nu)} = -\frac{1}{Mx}\left[\ln \prod_{i=1}^{M}\left(\frac{H_i^{tg}}{H_i^{og}}\right) - M \ln\left(\frac{1}{M}\sum_{i=1}^{M}\frac{H_i^{tv}}{H_i^{ov}}\right)\right]$$

or

$$\overline{\alpha^g(\nu)} = -\frac{1}{Mx}\left[\ln \prod_{i=1}^{M}\frac{H_i^{tg}}{H_i^{og}} - M \ln \sum_{i=1}^{M}\frac{H_i^{tv}}{H_i^{ov}} + M \ln M\right]$$

It follows that

$$\overline{\alpha^g(\nu)} = \frac{1}{x}\left[\ln \overline{\left(\frac{H^{tv}}{H^{ov}}\right)} - \ln \overline{\left(\frac{H^{tg}}{H^{og}}\right)}\right]$$

where

$$\ln \overline{\left(\frac{H^{tv}}{H^{ov}}\right)} = \ln\left[\frac{1}{M}\sum_{i=1}^{M}\left(\frac{H_i^{tv}}{H_i^{ov}}\right)\right]$$

and

$$\overline{\ln\left(\frac{H^{tg}}{H^{og}}\right)} = \frac{1}{M}\sum_{i=1}^{M}\ln\left(\frac{H_i^{tg}}{H_i^{og}}\right)$$

The transmission τ_i for a given path length x_i is given by

$$\tau_i = e^{-\overline{\alpha^g(\nu)}x_i}$$

Under the assumed conditions it is to be noted that the average absorption coefficient $\overline{\alpha^g(\nu)}$ is independent of detector characteristics R_i.

6. RESULTS

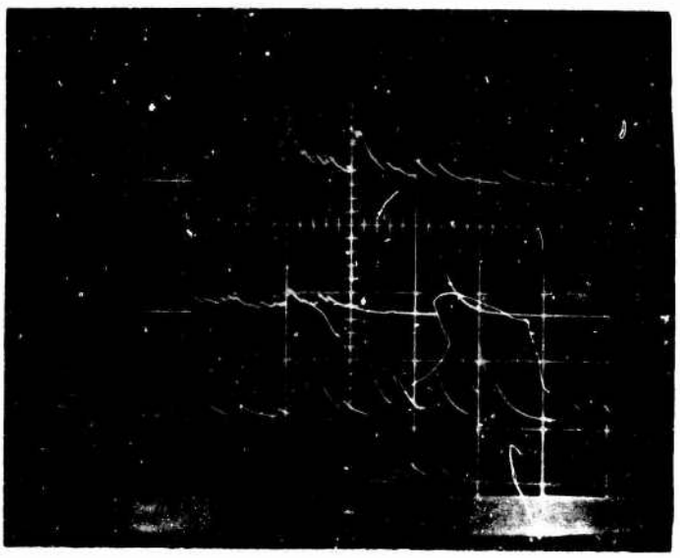
6.1. Spectral Measurements

The wavelength of the erbium laser emission, obtained from initial spectral measurements, was 1.544 ± 0.0005μ with a full width at half maximum of about 0.0015μ. The cylindrical rod-helical flash lamp configuration was used with 99%/95% reflectance wedge dielectric reflectors. This configuration was used for several hundred laser firings and for the initial absorption measurements. The threshold for laser oscillation was about 900 joules. It was subsequently learned that other investigators (18) were obtaining emission at 1.536μ from similar laser rods. The difference between the experimental results was apparently due to the efficiencies of the cavities used by the different investigators. The output reflector was therefore changed to first 80% reflectance and then 50% reflectance (aluminum-coated flats). The emission obtained with the 80% output reflector was still at 1.544μ but with a higher threshold. With the 50% output reflector, however, emission was obtained at 1.536μ with a threshold of about 1300 joules. By choosing the cavity losses appropriately, it was also possible to obtain both wavelengths at once.† The two laser emission lines are shown in Fig. 9; the upper two traces are at 1.536μ and the bottom two are at 1.544μ. The fact that both wavelengths were obtained with the 95% output reflector, whereas initially only the 1.544μ line was obtained, is due to additional cavity losses introduced, in time, by pits forming on the rod ends.

It was observed during these measurements that the surface of the rod slowly deteriorated and the ends became pitted. Figure 10 shows the effects of pitting. Figure 10a is a photograph taken under 50X magnification of one end of the rod after about 125 firings and Fig. 10b shows the same area after about 400 firings. The pits had the effect of lowering the efficiency of the cavity so that eventually laser oscillation was not obtainable at the 1.544μ line and finally ceased altogether (maximum pump attempted 1800 joules). The rectangular rods were then used, and oscillation has been obtained at both wavelengths separately and simultaneously.

---

†Simultaneous within the time resolution available ($\approx 10^{-6}$ sec).



λ 1.536 μ, .5V/cm

λ 1.536 μ, .5V/cm

λ 1.544 μ, .5V/cm

λ 1.544 μ, .2V/cm

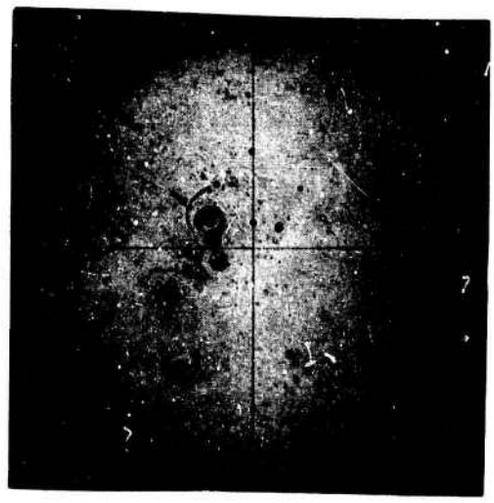
Pump: 1450 joules

Reflectance: 99%/95%

Sweep Rate: 0.5 millisec/cm

FIGURE 9. Simultaneous Emission of lines at 1.544 and 1.536 μ.

(a) 125 firings, 50X magnification



(b) 400 firings, 50X magnification

FIGURE 10. Effects of Pitting

In order to retard the degradation of the laser rods, careful cleaning of their surfaces and shielding of their ends from the flash lamp output was necessary. The cleaning procedure consisted of washing the rods with a mild soap and water solution, rinsing with distilled water, and then baking at around 50°C under about 100 torr pressure for one to two hours. A more detailed discussion of this problem has been published elsewhere (19).

6.2. Cell Measurements

The aerosol contribution to the attenuation in the cell was investigated by measuring the dust concentration in the cell with a Royco particle counter. This was done by flowing clean dry nitrogen through the cell and then sampling directly in the cell with the Royco. It was found that there were fewer than 1.76×10^4 particles/m^3 (500 particles/ft^3) with a diameter larger than 0.3 micron, fewer than 4.24×10^3 particles/m^3 (120 particles/ft^3) larger than 0.5 micron, and none larger than 5 microns. Under good atmospheric conditions the concentrations are at least 1000 times larger and result in about 10% loss per km of 1.54 micron radiation. Therefore, the aerosol attenuation in the cell is negligible.

Erbium laser atmospheric absorption measurements in clean dry air (78% N_2, 21% O_2, 0.2% CO_2, and noble gases) were made with path lengths varying from 400 to 1600 meters, a cell temperature normally around 37°C, and a cell pressure of 660 torr. Since the aerosol attenuation was shown to be negligible, the average absorption coefficient

---

$\alpha^g(\nu)$ was determined from these measurements as outlined in Section 5. The transmission obtained using this average absorption coefficient was 87% ± 10% per km.

7. SUMMARY

A new emission line of the erbium laser at 1.544μ and the simultaneous emission of lines at 1.544μ and 1.536μ are reported. Preliminary absorption measurements using clean dry air yielded a transmission of 87% ± 10% per km of 1.54 micron radiation.

A laboratory facility for the investigation of the absorption of electromagnetic energy by simulated atmospheres is also described. The facility consists of a combined 3.3-meter grating spectrograph-monochromator and a 20-meter multipass absorption cell. Control of the temperature, pressure, humidity, and gaseous composition of the medium under study is provided.

REFERENCES

1. R. E. Bruce, J. B. Mason, K. O. White, and R. B. Gomez, U. S. Army Electronics Command Report No. ECOM-5185, 1968 (AD-670934).

2. O. C. Mohler, A. K. Pierce, R. R. McMath, and L. Goldberg, Photometric Atlas of the Near Infrared Solar Spectrum λ8465 to λ25242 (University of Michigan Press, 1950).

3. D. M. Gates and W. J. Harrop, Appl. Optics 2, 887 (Sept. 1963).

4. G. E. Berlinguette and P. A. Tate, Canadian Defense Research Chemical Laboratory Report No. 420, 1963 (Proj. No. D-89-16-80-31).

5. J. H. Taylor and H. W. Yates, J. Opt. Soc. Am. 47, 223 (1957).

6. H. W. Yates and J. H. Taylor, U. S. Naval Research Laboratory Report No. 5453.

7. H. W. Yates, U. S. Naval Research Laboratory Report No. 5033.

8. L. Elterman, AFCRL Environmental Research Papers No. 46, Sept. 1964 (AD-607859).

9. G. B. Hoidale, S. M. Smith, A. J. Blanco and T. L. Barber, U. S. Army Electronics Command Report No. ECOM-5067, 1967 (AD-654990).

10. H. J. Bernstein and G. Herzberg, J. Chem. Phys. 16. 30 (Jan. 1948).

11. R. G. Pilston and J. U. White, J. Opt. Soc. Am. 44, 572 (July 1954).

12. J. U. White and N. L. Alpert, J. Opt. Soc. Am. 48, 460 (July 1958).

13. D. E. Burch, D. Gryvnak, and R. R. Patty, J. Opt. Soc. Am. 57, 885 (July 1967).

14. R. K. Long, Report by the Ohio State University Research Foundation May 1963 (AD-410571).

15. J. U. White, J. Opt. Soc. Am. 32, 285 (May 1942).

16. T. H. Edwards, J. Opt. Soc. Am. 51, 98 (Jan. 1961).

17. T. R. Reesor, J. Opt. Soc. Am. 41, 1059 (Dec. 1951).

18. E. Snitzer - Private Communication.

19. T. L. Barber, U. S. Army Electronics Command Report No. ECOM-5237, March 1969.

ATMOSPHERIC SCIENCES RESEARCH PAPERS

1. Webb, W.L., "Development of Droplet Size Distributions in the Atmosphere," June 1954.
2. Hansen, F. V., and H. Rachele, "Wind Structure Analysis and Forecasting Methods for Rockets," June 1954.
3. Webb, W. L., "Net Electrification of Water Droplets at the Earth's Surface," *J. Meteorol.*, December 1954.
4. Mitchell, R., "The Determination of Non-Ballistic Projectile Trajectories," March 1955.
5. Webb, W. L., and A. McPike, "Sound Ranging Technique for Determining the Trajectory of Supersonic Missiles," #1, March 1955.
6. Mitchell, R., and W. L. Webb, "Electromagnetic Radiation through the Atmosphere," #1, April 1955.
7. Webb, W. L., A. McPike, and H. Thompson, "Sound Ranging Technique for Determining the Trajectory of Supersonic Missiles," #2, July 1955.
8. Barichivich, A., "Meteorological Effects on the Refractive Index and Curvature of Microwaves in the Atmosphere," August 1955.
9. Webb, W. L., A. McPike and H. Thompson, "Sound Ranging Technique for Determining the Trajectory of Supersonic Missiles," #3, September 1955.
10. Mitchell, R., "Notes on the Theory of Longitudinal Wave Motion in the Atmosphere," February 1956.
11. Webb, W. L., "Particulate Counts in Natural Clouds," *J. Meteorol.*, April 1956.
12. Webb, W. L., "Wind Effect on the Aerobee," #1, May 1956.
13. Rachele, H., and L. Anderson, "Wind Effect on the Aerobee," #2, August 1956.
14. Beyers, N., "Electromagnetic Radiation through the Atmosphere," #2, January 1957.
15. Hansen, F. V., "Wind Effect on the Aerobee," #3, January 1957.
16. Kershner, J., and H. Bear, "Wind Effect on the Aerobee," #4, January 1957.
17. Hoidale, G., "Electromagnetic Radiation through the Atmosphere," #3, February 1957.
18. Querfeld, C. W., "The Index of Refraction of the Atmosphere for 2.2 Micron Radiation," March 1957.
19. White, Lloyd, "Wind Effect on the Aerobee," #5, March 1957.
20. Kershner, J. G., "Development of a Method for Forecasting Component Ballistic Wind," August 1957.
21. Layton, Ivan, "Atmospheric Particle Size Distribution," December 1957.
22. Rachele, Henry and W. H. Hatch, "Wind Effect on the Aerobee," #6, February 1958.
23. Beyers, N. J., "Electromagnetic Radiation through the Atmosphere," #4, March 1958.
24. Prosser, Shirley J., "Electromagnetic Radiation through the Atmosphere," #5, April 1958.
25. Armendariz, M., and P. H. Taft, "Double Theodolite Ballistic Wind Computations," June 1958.
26. Jenkins, K. R. and W. L. Webb. "Rocket Wind Measurements," June 1958.
27. Jenkins, K. R., "Measurement of High Altitude Winds with Loki," July 1958.
28. Hoidale, G., "Electromagnetic Propagation through the Atmosphere," #6, February 1959.
29. McLardie, M., R. Helvey, and L. Traylor, "Low-Level Wind Profile Prediction Techniques," #1, June 1959.
30. Lamberth, Roy, "Gustiness at White Sands Missile Range," #1, May 1959.
31. Beyers, N. J., B. Hinds, and G. Hoidale, "Electromagnetic Propagation through the Atmosphere," #7, June 1959.
32. Beyers, N. J., "Radar Refraction at Low Elevation Angles (U)," Proceedings of the Army Science Conference, June 1959.
33. White, L., O. W. Thiele and P. H. Taft, "Summary of Ballistic and Meteorological Support During IGY Operations at Fort Churchill, Canada," August 1959.
34. Hainline, D. A., "Drag Cord-Aerovane Equation Analysis for Computer Application," August 1959.
35. Hoidale, G. B., "Slope-Valley Wind at WSMR," October 1959.
36. Webb, W. L., and K. R. Jenkins, "High Altitude Wind Measurements," *J. Meteorol.*, 16, 5, October 1959.

37. White, Lloyd, "Wind Effect on the Aerobee," #9, October 1959.
38. Webb, W. L., J. W. Coffman, and G. Q. Clark, "A High Altitude Acoustic Sensing System," December 1959.
39. Webb, W. L., and K. R. Jenkins, "Application of Meteorological Rocket Systems," J. Geophys. Res., 64, 11, November 1959.
40. Duncan, Louis, "Wind Effect on the Aerobee," #10, February 1960.
41. Helvey, R. A., "Low-Level Wind Profile Prediction Techniques," #2, February 1960.
42. Webb, W. L., and K. R. Jenkins, "Rocket Sounding of High-Altitude Parameters," *Proc. GM Rel. Symp.*, Dept. of Defense, February 1960.
43. Armendariz, M., and H. H. Monahan, "A Comparison Between the Double Theodolite and Single-Theodolite Wind Measuring Systems," April 1960.
44. Jenkins, K. R., and P. H. Taft, "Weather Elements in the Tularosa Basin," July 1960.
45. Beyers, N. J., "Preliminary Radar Performance Data on Passive Rocket-Borne Wind Sensors," IRE TRANS, MIL ELECT, MIL-4, 2-3, April-July 1960.
46. Webb, W. L., and K. R. Jenkins, "Speed of Sound in the Stratosphere," June 1960.
47. Webb, W. L., K. R. Jenkins, and G. Q. Clark, "Rocket Sounding of High Atmosphere Meteorological Parameters," *IRE Trans. Mil. Elect.*, MIL-4, 2-3, April-July 1960.
48. Helvey, R. A., "Low-Level Wind Profile Prediction Techniques," #3, September 1960.
49. Beyers, N. J., and O. W. Thiele, "Meteorological Wind Sensors," August 1960.
50. Armijo, Larry, "Determination of Trajectories Using Range Data from Three Noncolinear Radar Stations," September 1960.
51. Carnes, Patsy Sue, "Temperature Variations in the First 200 Feet of the Atmosphere in an Arid Region," July 1961.
52. Springer, H. S., and R. O. Olsen, "Launch Noise Distribution of Nike-Zeus Missiles," July 1961.
53. Thiele, O. W., "Density and Pressure Profiles Derived from Meteorological Rocket Measurements," September 1961.
54. Diamond, M. and A. B. Gray, "Accuracy of Missile Sound Ranging," November 1961.
55. Lamberth, R. L. and D. R. Veith, "Variability of Surface Wind in Short Distances," #1, October 1961.
56. Swanson, R. N., "Low-Level Wind Measurements for Ballistic Missile Application," January 1962.
57. Lamberth, R. L. and J. H. Grace, "Gustiness at White Sands Missile Range," #2, January 1962.
58. Swanson, R. N. and M. M. Hoidale, "Low-Level Wind Profile Prediction Techniques," #4, January 1962.
59. Rachele, Henry, "Surface Wind Model for Unguided Rockets Using Spectrum and Cross Spectrum Techniques." January 1962.
60. Rachele, Henry, "Sound Propagation through a Windy Atmosphere," #2, February 1962.
61. Webb, W. L., and K. R. Jenkins, "Sonic Structure of the Mesosphere," *J. Acous. Soc. Amer.*, 34, 2, February 1962.
62. Tourin, M. H. and M. M. Hoidale, "Low-Level Turbulence Characteristics at White Sands Missile Range," April 1962.
63. Miers, Bruce T., "Mesospheric Wind Reversal over White Sands Missile Range," March 1962.
64. Fisher, E., R. Lee and H. Rachele, "Meteorological Effects on an Acoustic Wave within a Sound Ranging Array," May 1962.
65. Walter, E. L., "Six Variable Ballistic Model for a Rocket," June 1962.
66. Webb, W. L., "Detailed Acoustic Structure Above the Tropopause," *J. Applied Meteorol.*, 1, 2, June 1962.
67. Jenkins, K. R., "Empirical Comparisons of Meteorological Rocket Wind Sensors," *J. Appl. Meteor.*, June 1962.
68. Lamberth, Roy, "Wind Variability Estimates as a Function of Sampling Interval," July 1962.
69. Rachele, Henry, "Surface Wind Sampling Periods for Unguided Rocket Impact Prediction," July 1962.
70. Traylor, Larry, "Coriolis Effects on the Aerobee-Hi Sounding Rocket," August 1962.
71. McCoy, J., and G. Q. Clark, "Meteorological Rocket Thermometry," August 1962.
72. Rachele, Henry, "Real-Time Prelaunch Impact Prediction System," August 1962.

73. Beyers, N. J., O. W. Thiele, and N. K. Wagner, "Performance Characteristics of Meteorlogical Rocket Wind and Temperature Sensors," October 1962.
74. Coffman, J., and R. Price, "Some Errors Associated with Acoustical Wind Measurements through a Layer," October 1962.
75. Armendariz, M., E. Fisher, and J. Serna, "Wind Shear in the Jet Stream at WSMR," November 1962.
76. Armendariz, M., F. Hansen, and S. Carnes, "Wind Variability and its Effect on Rocket Impact Prediction," January 1963.
77. Querfeld, C., and Wayne Yunker, "Pure Rotational Spectrum of Water Vapor, I: Table of Line Parameters," February 1963.
78. Webb, W. L., "Acoustic Component of Turbulence," *J. Applied Meteorol.*, 2, 2, April 1963.
79. Beyers, N. and L. Engberg, "Seasonal Variability in the Upper Atmosphere," May 1963.
80. Williamson, L. E., "Atmospheric Acoustic Structure of the Sub-polar Fall," May 1963.
81. Lamberth, Roy and D. Veith, "Upper Wind Correlations in Southwestern United States," June 1963.
82. Sandlin, E., "An analysis of Wind Shear Differences as Measured by AN/FPS-16 Radar and AN/GMD-1B Rawinsonde," August 1963.
83. Diamond, M. and R. P. Lee, "Statistical Data on Atmospheric Design Properties Above 30 km," August 1963.
84. Thiele, O. W., "Mesospheric Density Variability Based on Recent Meteorological Rocket Measurements," *J. Applied Meteorol.*, 2, 5, October 1963.
85. Diamond, M., and O. Essenwanger, "Statistical Data on Atmospheric Design Properties to 30 km," *Astro. Aero. Engr.*, December 1963.
86. Hansen, F. V., "Turbulence Characteristics of the First 62 Meters of the Atmosphere," December 1963.
87. Morris, J. E., and B. T. Miers, "Circulation Disturbances Between 25 and 70 kilometers Associated with the Sudden Warming of 1963," *J. of Geophys. Res.*, January 1964.
88. Thiele, O. W., "Some Observed Short Term and Diurnal Variations of Stratospheric Density Above 30 km," January 1964.
89. Sandlin, R. E., Jr. and E. Armijo, "An Analysis of AN/FPS-16 Radar and AN/GMD-1B Rawinsonde Data Differences," January 1964.
90. Miers, B. T., and N. J. Beyers, "Rocketsonde Wind and Temperature Measurements Between 30 and 70 km for Selected Stations," *J. Applied Meteorol.*, February 1964.
91. Webb, W. L., "The Dynamic Stratosphere," *Astronautics and Aerospace Engineering*, March 1964.
92. Low, R. D. H., "Acoustic Measurements of Wind through a Layer," March 1964.
93. Diamond. M., "Cross Wind Effect on Sound Propagation," *J. Applied Meteorol.*, April 1964.
94. Lee, R. P., "Acoustic Ray Tracing," April 1964.
95. Reynolds, R. D., "Investigation of the Effect of Lapse Rate on Balloon Ascent Rate," May 1964.
96. Webb, W. L., "Scale of Stratospheric Detail Structure," *Space Research V*, May 1964.
97. Barber, T. L., "Proposed X-Ray-Infrared Method for Identification of Atmospheric Mineral Dust," June 1964.
98. Thiele, O. W., "Ballistic Procedures for Unguided Rocket Studies of Nuclear Environments (U)," Proceedings of the Army Science Conference, June 1964.
99. Horn, J. D., and E. J. Trawle, "Orographic Effects on Wind Variability," July 1964.
100. Hoidale, G., C. Querfeld, T. Hall, and R. Mireles, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," #1, September 1964.
101. Duncan, L. D., R. Ensey, and B. Engebos, "Athena Launch Angle Determination," September 1964.
102. Thiele, O. W., "Feasibility Experiment for Measuring Atmospheric Density Through the Altitude Range of 60 to 100 KM Over White Sands Missile Range," October 1964.
103. Duncan, L. D., and R. Ensey, "Six-Degree-of-Freedom Digital Simulation Model for Unguided, Fin-Stabilized Rockets," November 1964.

104. Hoidale, G., C. Querfeld, T. Hall, and R. Mireles, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," #2, November 1964.
105. Webb, W. L., "Stratospheric Solar Response," *J. Atmos. Sci.*, November 1964.
106. McCoy, J. and G. Clark, "Rocketsonde Measurement of Stratospheric Temperature," December 1964.
107. Farone, W. A., "Electromagnetic Scattering from Radially Inhomogeneous Spheres as Applied to the Problem of Clear Atmosphere Radar Echoes," December 1964.
108. Farone, W. A., "The Effect of the Solid Angle of Illumination or Observation on the Color Spectra of 'White Light' Scattered by Cylinders," January 1965.
109. Williamson, L. E., "Seasonal and Regional Characteristics of Acoustic Atmospheres," *J. Geophys. Res.*, January 1965.
110. Armendariz, M., "Ballistic Wind Variability at Green River, Utah," January 1965.
111. Low, R. D. H., "Sound Speed Variability Due to Atmospheric Composition," January 1965.
112. Querfeld, C. W., 'Mie Atmospheric Optics," *J. Opt. Soc. Amer.*, January 1965.
113. Coffman, J., "A Measurement of the Effect of Atmospheric Turbulence on the Coherent Properties of a Sound Wave," January 1965.
114. Rachele, H., and D. Veith, "Surface Wind Sampling for Unguided Rocket Impact Prediction," January 1965.
115. Ballard, H., and M. Izquierdo, "Reduction of Microphone Wind Noise by the Generation of a Proper Turbulent Flow," February 1965.
116. Mireles, R., "An Algorithm for Computing Half Widths of Overlapping Lines on Experimental Spectra," February 1965.
117. Richart, H., "Inaccuracies of the Single-Theodolite Wind Measuring System in Ballistic Application," February 1965.
118. D'Arcy, M., "Theoretical and Practical Study of Aerobee-150 Ballistics," March 1965.
119. McCoy, J., "Improved Method for the Reduction of Rocketsonde Temperature Data," March 1965.
120. Mireles, R., "Uniqueness Theorem in Inverse Electromagnetic Cylindrical Scattering," April 1965.
121. Coffman, J., "The Focusing of Sound Propagating Vertically in a Horizontally Stratified Medium," April 1965.
122. Farone, W. A., and C. Querfeld, "Electromagnetic Scattering from an Infinite Circular Cylinder at Oblique Incidence." April 1965.
123. Rachele, H., "Sound Propagation through a Windy Atmosphere," April 1965.
124. Miers, B., "Upper Stratospheric Circulation over Ascension Island," April 1965.
125. Rider, L., and M. Armendariz, " A Comparison of Pibal and Tower Wind Measurements," April 1965.
126. Hoidale, G. B., "Meteorological Conditions Allowing a Rare Observation of 24 Micron Solar Radiation Near Sea Level," *Meteorol. Magazine*, May 1965.
127. Beyers, N. J., and B. T. Miers, "Diurnal Temperature Change in the Atmosphere Between 30 and 60 km over White Sands Missile Range," *J. Atmos. Sci.*, May 1965.
128. Querfeld, C., and W. A. Farone, "Tables of the Mie Forward Lobe," May 1965.
129. Farone, W. A., Generalization of Rayleigh-Gans Scattering from Radially Inhomogeneous Spheres," *J. Opt. Soc. Amer.*, June 1965.
130. Diamond, M., "Note on Mesospheric Winds Above White Sands Missile Range," *J. Applied Meteorol.*, June 1965.
131. Clark, G. Q., and J. G. McCoy, "Measurement of Stratospheric Temperature," *J. Applied Meteorol.*, June 1965.
132. Hall, T., G. Hoidale, R. Mireles, and C. Querfeld, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," #3, July 1965.
133. McCoy, J., and C. Tate, "The Delta-T Meteorological Rocket Payload," June 1964.
134. Horn, J. D., "Obstacle Influence in a Wind Tunnel," July 1965.
135. McCoy, J., "An AC Probe for the Measurement of Electron Density and Collision Frequency in the Lower Ionosphere," July 1965.
136. Miers, B. T., M. D. Kays, O. W. Thiele and E. M. Newby, "Investigation of Short Term Variations of Several Atmospheric Parameters Above 30 KM," July 1965.

137. Serna, J., "An Acoustic Ray Tracing Method for Digital Computation," September 1965.
138. Webb, W. L., "Morphology of Noctilucent Clouds," *J. Geophys. Res.*, 70, 18, 4463-4475, September 1965.
139. Kays, M., and R. A. Craig, "On the Order of Magnitude of Large-Scale Vertical Motions in the Upper Stratosphere," *J. Geophys. Res.*, 70, 18, 4453-4462, September 1965.
140. Rider, L., "Low-Level Jet at White Sands Missile Range," September 1965.
141. Lamberth, R. L., R. Reynolds, and Morton Wurtele, "The Mountain Lee Wave at White Sands Missile Range," *Bull. Amer. Meteorol. Soc.*, 46, 10, October 1965.
142. Reynolds, R. and R. L. Lamberth, "Ambient Temperature Measurements from Radiosondes Flown on Constant-Level Balloons," October 1965.
143. McCluney, E., "Theoretical Trajectory Performance of the Five-Inch Gun Probe System," October 1965.
144. Pena, R. and M. Diamond, "Atmospheric Sound Propagation near the Earth's Surface," October 1965.
145. Mason, J. B., "A Study of the Feasibility of Using Radar Chaff For Stratospheric Temperature Measurements," November 1965.
146. Diamond, M., and R. P. Lee, "Long-Range Atmospheric Sound Propagation," *J. Geophys. Res.*, 70, 22, November 1965.
147. Lamberth, R. L., "On the Measurement of Dust Devil Parameters," November 1965.
148. Hansen, F. V., and P. S. Hansen, "Formation of an Internal Boundary over Heterogeneous Terrain," November 1965.
149. Webb, W. L., "Mechanics of Stratospheric Seasonal Reversals," November 1965.
150. U. S. Army Electronics R & D Activity, "U. S. Army Participation in the Meteorological Rocket Network," January 1966.
151. Rider, L. J., and M. Armendariz, "Low-Level Jet Winds at Green River, Utah," February 1966.
152. Webb, W. L., "Diurnal Variations in the Stratospheric Circulation," February 1966.
153. Beyers, N. J., B. T. Miers, and R. J. Reed, "Diurnal Tidal Motions near the Stratopause During 48 Hours at WSMR," February 1966.
154. Webb, W. L., "The Stratospheric Tidal Jet," February 1966.
155. Hall, J. T., "Focal Properties of a Plane Grating in a Convergent Beam," February 1966.
156. Duncan, L. D., and Henry Rachele, "Real-Time Meteorological System for Firing of Unguided Rockets," February 1966.
157. Kays, M. D., "A Note on the Comparison of Rocket and Estimated Geostrophic Winds at the 10-mb Level," *J. Appl. Meteor.*, February 1966.
158. Rider, L., and M. Armendariz, " A Comparison of Pibal and Tower Wind Measurements," *J. Appl. Meteor.*, 5, February 1966.
159. Duncan, L. D., "Coordinate Transformations in Trajectory Simulations," February 1966.
160. Williamson, L. E., "Gun-Launched Vertical Probes at White Sands Missile Range," February 1966.
161. Randhawa, J. S., Ozone Measurements with Rocket-Borne Ozonesondes," March 1966.
162. Armendariz, Manuel, and Laurence J. Rider, "Wind Shear for Small Thickness Layers," March 1966.
163. Low, R. D. H., "Continuous Determination of the Average Sound Velocity over an Arbitrary Path," March 1966.
164. Hansen, Frank V., "Richardson Number Tables for the Surface Boundary Layer," March 1966.
165. Cochran, V. C., E. M. D'Arcy, and Florencio Ramirez, "Digital Computer Program for Five-Degree-of-Freedom Trajectory," March 1966.
166. Thiele, O. W., and N. J. Beyers, "Comparison of Rocketsonde and Radiosonde Temperatures and a Verification of Computed Rocketsonde Pressure and Density," April 1966.
167. Thiele, O. W., "Observed Diurnal Oscillations of Pressure and Density in the Upper Stratosphere and Lower Mesosphere," April 1966.
168. Kays, M. D., and R. A. Craig, "On the Order of Magnitude of Large-Scale Vertical Motions in the Upper Stratosphere," *J. Geophy. Res.*, April 1966.
169. Hansen, F. V., "The Richardson Number in the Planetary Boundary Layer," May 1966.

170. Ballard, H. N., "The Measurement of Temperature in the Stratosphere and Mesosphere," June 1966.
171. Hansen, Frank V., "The Ratio of the Exchange Coefficients for Heat and Momentum in a Homogeneous, Thermally Stratified Atmosphere," June 1966.
172. Hansen, Frank V., "Comparison of Nine Profile Models for the Diabatic Boundary Layer," June 1966.
173. Rachele, Henry, "A Sound-Ranging Technique for Locating Supersonic Missiles," May 1966.
174. Farone, W. A., and C. W. Querfeld. "Electromagnetic Scattering from Inhomogeneous Infinite Cylinders at Oblique Incidence," *J. Opt. Soc. Amer.* 56, 4, 476-480, April 1966.
175. Mireles, Ramon, "Determination of Parameters in Absorption Spectra by Numerical Minimization Techniques." *J. Opt. Soc. Amer.* 56, 5, 644-647, May 1966.
176. Reynolds, R., and R. L. Lamberth, "Ambient Temperature Measurements from Radiosondes Flown on Constant-Level Balloons," *J. Appl. Meteorol.*, 5, 3, 304-307, June 1966.
177. Hall, James T., "Focal Properties of a Plane Grating in a Convergent Beam," *Appl. Opt.*, 5, 1051, June 1966
178. Rider, Laurence J., "Low-Level Jet at White Sands Missile Range," *J. Appl. Meteorol.*, 5, 3, 283-287, June 1966.
179. McCluney, Eugene, "Projectile Dispersion as Caused by Barrel Displacement in the 5-Inch Gun Probe System," July 1966.
180. Armendariz, Manuel, and Laurence J. Rider, "Wind Shear Calculations for Small Shear Layers," June 1966.
181. Lamberth, Roy L., and Manuel Armendariz, "Upper Wind Correlations in the Central Rocky Mountains," June 1966.
182. Hansen, Frank V., and Virgil D. Lang, "The Wind Regime in the First 62 Meters of the Atmosphere," June 1966.
183. Randhawa, Jagir S., "Rocket-Borne Ozonesonde," July 1966.
184. Rachele, Henry, and L. D. Duncan, "The Desirability of Using a Fast Sampling Rate for Computing Wind Velocity from Pilot-Balloon Data," July 1966.
185. Hinds, B. D., and R. G. Pappas, "A Comparison of Three Methods for the Correction of Radar Elevation Angle Refraction Errors," August 1966.
186. Riedmuller, G. F., and T. L. Barber, "A Mineral Transition in Atmospheric Dust Transport," August 1966.
187. Hall, J. T., C. W. Querfeld, and G. B. Hoidale, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," Part IV (Final), July 1966.
188. Duncan, L. D. and B. F. Engebos, "Techniques for Computing Launcher Settings for Unguided Rockets," September 1966.
189. Duncan, L. D., "Basic Considerations in the Development of an Unguided Rocket Trajectory Simulation Model," September 1966.
190. Miller, Walter B., "Consideration of Some Problems in Curve Fitting," September 1966.
191. Cermak, J. E., and J. D. Horn, "The Tower Shadow Effect," August 1966.
192. Webb, W. L., "Stratospheric Circulation Response to a Solar Eclipse," October 1966.
193. Kennedy, Bruce, "Muzzle Velocity Measurement," October 1966.
194. Traylor, Larry E., "A Refinement Technique for Unguided Rocket Drag Coefficients," October 1966
195. Nusbaum, Henry, "A Reagent for the Simultaneous Microscope Determination of Quartz and Halides," October 1966.
196. Kays, Marvin and R. O. Olsen, "Improved Rocketsonde Parachute-derived Wind Profiles," October 1966.
197. Engebos, Bernard F. and Duncan, Louis D., "A Nomogram for Field Determination of Launcher Angles for Unguided Rockets," October 1966.
198. Webb, W. L., "Midlatitude Clouds in the Upper Atmosphere," November 1966.
199. Hansen, Frank V., "The Lateral Intensity of Turbulence as a Function of Stability," November 1966.
200. Rider, L. J. and M. Armendariz, "Differences of Tower and Pibal Wind Profiles," November 1966.
201. Lee, Robert P., "A Comparison of Eight Mathematical Models for Atmospheric Acoustical Ray Tracing," November 1966.
202. Low, R. D. H., et al., "Acoustical and Meteorological Data Report SOTRAN I and II," November 1966.

203. Hunt, J. A. and J. D. Horn, "Drag Plate Balance," December 1966.
204. Armendariz, M., and H. Rachele, "Determination of a Representative Wind Profile from Balloon Data," December 1966.
205. Hansen, Frank V., "The Aerodynamic Roughness of the Complex Terrain of White Sands Missile Range," January 1967.
206. Morris, James E., "Wind Measurements in the Subpolar Mesopause Region," January 1967.
207. Hall, James T., "Attenuation of Millimeter Wavelength Radiation by Gaseous Water," January 1967.
208. Thiele, O. W., and N. J. Beyers, "Upper Atmosphere Pressure Measurements With Thermal Conductivity Gauges," January 1967.
209. Armendariz, M., and H. Rachele, "Determination of a Representative Wind Profile from Balloon Data," January 1967.
210. Hansen, F. V., "The Aerodynamic Roughness of the Complex Terrain of White Sands Missile Range, New Mexico," January 1967.
211. D'Arcy, Edward M., "Some Applications of Wind to Unguided Rocket Impact Prediction," March 1967.
212. Kennedy, Bruce, "Operation Manual for Stratosphere Temperature Sonde," March 1967.
213. Hoidale, G. B., S. M. Smith, A. J. Blanco, and T. L. Barber, "A Study of Atmospheric Dust," March 1967.
214. Longyear, J. Q., "An Algorithm for Obtaining Solutions to Laplace's Titad Equations," March 1967.
215. Rider, L. J., "A Comparison of Pibal with Raob and Rawin Wind Measurements," April 1967.
216. Breeland, A. H., and R. S. Bonner, "Results of Tests Involving Hemispherical Wind Screens in the Reduction of Wind Noise," April 1967.
217. Webb, Willis L., and Max C. Bolen, "The D-region Fair-Weather Electric Field," April 1967.
218. Kubinski, Stanley F., "A Comparative Evaluation of the Automatic Tracking Pilot-Balloon Wind Measuring System," April 1967.
219. Miller, Walter B., and Henry Rachele, "On Nonparametric Testing of the Nature of Certain Time Series," April 1967.
220. Hansen, Frank V., "Spacial and Temporal Distribution of the Gradient Richardson Number in the Surface and Planetary Layers," May 1967.
221. Randhawa, Jagir S., "Diurnal Variation of Ozone at High Altitudes," May 1967.
222. Ballard, Harold N., "A Review of Seven Papers Concerning the Measurement of Temperature in the Stratosphere and Mesosphere," May 1967.
223. Williams, Ben H., "Synoptic Analyses of the Upper Stratospheric Circulation During the Late Winter Storm Period of 1966," May 1967.
224. Horn, J. D., and J. A. Hunt, "System Design for the Atmospheric Sciences Office Wind Research Facility," May 1967.
225. Miller, Walter B., and Henry Rachele, "Dynamic Evaluation of Radar and Photo Tracking Systems, " May 1967.
226. Bonner, Robert S., and Ralph H. Rohwer, "Acoustical and Meteorological Data Report - SOTRAN III and IV," May 1967.
227. Rider, L. J., "On Time Variability of Wind at White Sands Missile Range, New Mexico," June 1967.
228. Randhawa, Jagir S., "Mesospheric Ozone Measurements During a Solar Eclipse," June 1967.
229. Beyers, N. J., and B. T. Miers, "A Tidal Experiment in the Equatorial Stratosphere over Ascension Island (8S)", June 1967.
230. Miller, W. B., and H. Rachele, "On the Behavior of Derivative Processes," June 1967
231. Walters, Randall K., "Numerical Integration Methods for Ballistic Rocket Trajectory Simulation Programs," June 1967.
232. Hansen, Frank V., "A Diabatic Surface Boundary Layer Model," July 1967.
233. Butler, Ralph L., and James K. Hall, "Comparison of Two Wind Measuring Systems with the Contraves Photo-Theodolite," July 1967.
234. Webb, Willis L., "The Source of Atmospheric Electrification," June 1967.

235. Hinds, B. D., "Radar Tracking Anomalies over an Arid Interior Basin," August 1967.
236. Christian, Larry O., "Radar Cross Sections for Totally Reflecting Spheres," August 196[illegible].
237. D'Arcy, Edward M., "Theoretical Dispersion Analysis of the Aerobee 350," August 1967.
238. Anon., "Technical Data Package for Rocket-Borne Temperature Sensor," August 1967.
239. Glass, Roy I., Roy L. Lamberth, and Ralph D. Reynolds, "A High Resolution Continuous Pressure Sensor Modification for Radiosondes," August 1967.
240. Low, Richard D. H., "Acoustic Measurement of Supersaturation in a Warm Cloud," August 1967.
241. Rubio, Roberto, and Harold N. Ballard, "Time Response and Aerodynamic Heating of Atmospheric Temperature Sensing Elements," August 1967.
242. Seagraves, Mary Ann B., "Theoretical Performance Characteristics and Wind Effects for the Aerobee 150," August 1967.
243. Duncan, Louis Dean, "Channel Capacity and Coding," August 1967.
244. Dunaway, G. L., and Mary Ann B. Seagraves, "Launcher Settings Versus Jack Settings for Aerobee 150 Launchers - Launch Complex 35, White Sands Missile Range, New Mexico," August 1967.
245. Duncan, Louis D., and Bernard F. Engebos, "A Six-Degree-of-Freedom Digital Computer Program for Trajectory Simulation," October 1967.
246. Rider, Laurence J., and Manuel Armendariz, "A Comparison of Simultaneous Wind Profiles Derived from Smooth and Roughened Spheres," September 1967.
247. Reynolds, Ralph D., Roy L. Lamberth, and Morton G. Wurtele, "Mountain Wave Theory vs Field Test Measurements," September 1967.
248. Lee, Robert P., "Probabilistic Model for Acoustic Sound Ranging," October 1967.
249. Williamson, L. Edwin, and Bruce Kennedy, "Meteorological Shell for Standard Artillery Pieces - A Feasibility Study," October 1967.
250. Rohwer, Ralph H., "Acoustical, Meteorological and Seismic Data Report - SOTRAN V and VI," October 1967.
251. Nordquist, Walter S., Jr., "A Study in Acoustic Direction Finding," November 1967.
252. Nordquist, Walter S., Jr., "A Study of Acoustic Monitoring of the Gun Probe System," November 1967.
253. Avara, E. P., and B. T. Miers, "A Data Reduction Technique for Meteorological Wind Data above 30 Kilometers," December 1967.
254. Hansen, Frank V., "Predicting Diffusion of Atmospheric Contaminants by Consideration of Turbulent Characteristics of WSMR," January 1968.
255. Randhawa, Jagir S., "Rocket Measurements of Atmospheric Ozone," January 1968.
256. D'Arcy, Edward M., "Meteorological Requirements for the Aerobee-350," January 1968.
257. D'Arcy, Edward M., "A Computer Study of the Wind Frequency Response of Unguided Rockets," February 1968.
258. Williamson, L. Edwin, "Gun Launched Probes - Parachute Expulsion Tests Under Simulated Environment," February 1968.
259. Beyers, Norman J., Bruce T. Miers, and Elton P. Avara, "The Diurnal Tide Near the Stratopause over White Sands Missile Range, New Mexico," February 1968.
260. Traylor, Larry E., "Preliminary Study of the Wind Frequency Response of the Honest John M50 Tactical Rocket," March 1968.
261. Engebos, B. F., and L. D. Duncan, "Real-Time Computations of Pilot Balloon Winds," March 1968.
262. Butler, Ralph and L. D. Duncan, "Empirical Estimates of Errors in Double-Theodolite Wind Measurements," February 1968.
263. Kennedy, Bruce, et al., "Thin Film Temperature Sensor," March 1968.
264. Bruce, Dr. Rufus, James Mason, Dr. Kenneth White and Richard B. Gomez, "An Estimate of the Atmospheric Propagation Characteristics of 1.54 Micron Laser Energy," March 1968.

265. Ballard, Harold N., Jagir S. Randhawa, and Willis L. Webb, "Stratospheric Circulation Response to a Solar Eclipse," March 1968.
266. Johnson, James L., and Orville C. Kuberski, "Timing Controlled Pulse Generator," April 1968.
267. Blanco, Abel J., and Glenn B. Hoidale, "Infrared Absorption Spectra of Atmospheric Dust," May 1968.
268. Jacobs, Willie N., "Automatic Pibal Tracking System," May 1968.
269. Morris, James E., and Marvin D. Kays, "Circulation in the Arctic Mesosphere in Summer," June 1968.
270. Mason, James B., "Detection of Atmospheric Oxygen Using a Tuned Ruby Laser," June 1968.
271. Armendariz, Manuel, and Virgil D. Lang, "Wind Correlation and Variability in Time and Space," July 1968.
272. Webb, Willis L., "Tropospheric Electrical Structure," July 1968.
273. Miers, Bruce T., and Elton P. Avara, "Analysis of High-Frequency Components of AN/FPS-16 Radar Data," August 1968.
274. Dunaway, Gordon L., "A Practical Field Wind Compensation Technique for Unguided Rockets," August 1968.
275. Seagraves, Mary Ann B., and Barry Butler, "Performance Characteristics and Wind Effects for the Aerobee 150 with VAM Booster," September 1968.
276. Low, Richard D. H., "A Generalized Equation for Droplet Growth Due to the Solution Effect," September 1968.
277. Jenkins, Kenneth R., "Meteorological Research, Development, Test, and Evaluation Rocket," September 1968.
278. Williams, Ben H., and Bruce T. Miers, "The Synoptic Events of the Stratospheric Warming of December 1967 - January 1968," September 1968.
279. Tate, C. L., and Bruce W. Kennedy, "Technical Data Package for Atmospheric Temperature Sensor Mini-Loki," September 1968.
280. Rider, Laurence J., Manuel Armendariz, and Frank V. Hansen, "A Study of Wind and Temperature Variability at White Sands Missile Range, New Mexico," September 1968.
281. Duncan, Louis D., and Walter B. Miller, "The Hull of a Channel," September 1968.
282. Hansen, Frank V., and Gary A. Ethridge, "Diffusion Nomograms and Tables for Rocket Propellants and Combustion By-Products," January 1968.
283. Walters, Randall K., and Bernard F. Engebos, "An Improved Method of Error Control for Runge-Kutta Numerical Integration," October 1968.
284. Miller, Walter B., "A Non-Entropy Approach to Some Topics in Channel Theory," November 1968.
285. Armendariz, Manuel, Laurence J. Rider, and Frank V. Hansen, "Turbulent Characteristics in the Surface Boundary Layer," November 1968.
286. Randhawa, Jagir S., "Rocket Measurements of the Diurnal Variation of Atmospheric Ozone," December 1968.
287. Randhawa, Jagir S., "A Guide to Rocketsonde Measurements of Atmospheric Ozone," January 1969.
288. Webb, Willis L., "Solar Control of the Stratospheric Circulation," February 1969.
289. Lee, Robert P., "A Dimensional Analysis of the Error of Atmospheric Sound Ranging," March 1969.
290. Barber, T. L., "Degradation of Laser Optical Surfaces," March 1969.
291. D'Arcy, E. M., "Diffusion of Resonance Excitation Through a One-Dimensional Gas," March 1969.
292. Randhawa, J. S., "Ozone Measurements from a Stable Platform near the Stratopause Level," March 1969.
293. Rubio, Roberto, "Faraday Rotation System for Measuring Electron Densities," March 1969.
294. Olsen, Robert, "A Design Plan for Investigating the Atmospheric Environment Associated with High Altitude Nuclear Testing," March 1969.
295. Monahan, H. H., M. Armendariz, and V. D. Lang, "Estimates of Wind Variability Between 100 and 900 Meters," April 1969.
296. Rinehart, G. S., "Fog Drop Size Distributions - Measurement Methods and Evaluation," April 1969.

297. D'Arcy, Edward M., and Henry Rachele, "Proposed Prelaunch Real-Time Impact Prediction System for the Aerobee-350 Rocket," May 1969.
298. Low, Richard D. H., "A Comprehensive Report on Nineteen Condensation Nuclei (Part I - Equilibrium Growth and Physical Properties)," May 1969.
299. Randhawa, J. S., "Vertical Distribution of Ozone in the Winter Subpolar Region," June 1969.
300. Rider, Laurence J., and Manuel Armendariz, "Vertical Wind Component Estimates up to 1.2km Above Ground, July 1969.
301. Duncan, L. D., and Bernard F. Engebos, "A Rapidly Converging Iterative Technique for Computing Wind Compensation Launcher Settings for Unguided Rockets," July 1969.
302. Gomez, R. B. and K. O. White, "Erbium Laser Propagation in Simulated Atmospheres I. Description of Experimental Apparatus and Preliminary Results," July 1969.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*

U. S. Army Electronics Command
Fort Monmouth, New Jersey

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

Erbium Laser Propagation in Simulated Atmospheres
I. Description of Experimental Apparatus and Preliminary Results

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

R. B. Gomez
K. O. White

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1969	25	19

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	ECOM - 5260
c. Task No. 1T061102B53A-10	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

Distribution of this report is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Atmospheric Sciences Laboratory U. S. Army Electronics Command White Sands Missile Range, New Mexico

13. ABSTRACT

Initial results are presented of an experimental study utilizing an absorption cell facility to determine erbium laser propagation characteristics in simulated atmospheres. The facility consists of a 3.3-meter spectrometer coupled to a 20-meter multipass absorption cell. The cell environment can be controlled over a wide range of pressures, temperatures, humidities, and gas concentrations. Absorption measurements were made with path lengths varying from 400 to 1600 meters in a simulated atmosphere consisting of clean dry air. The initial experimentally measured attenuation of 1.54 micron radiation by clean dry air is less than 25% per km. The results include the discovery of a new emission line of the erbium laser at 1.544 microns and the simultaneous emission of lines at 1.544 and 1.536 microns.

DD FORM 1 NOV 68 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Absorption Cell Facility						
2. 1.54 Micron Radiation						
3. Erbium Laser						
4. Absorption						
5. Scattering						

UNCLASSIFIED

Security Classification

AFLC/HAFB, Ogden